ECONOMICS OF CELLULOSIC ETHANOL PRODUCTION: GREEN LIQUOR PRETREATMENT FOR SOFTWOOD AND HARDWOOD, GREENFIELD AND REPURPOSE SCENARIOS

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Green liquor pretreatment, a technology presently used worldwide in hundreds of kraft pulp mills, is proposed in this work as a potential pretreatment pathway for the efficient conversion of lignocellulosic biomass into ethanol. Mixed southern hardwood, eucalyptus, and loblolly pine were evaluated through process simulations in two investment scenarios: a greenfield mill scenario and a repurposing scenario, using existing kraft pulp mill assets for cellulosic ethanol production. Several advantages come with this concept: i) proven technology (both process and equipment), ii) chemical and energy recovery in place, iii) existing fiber supply chain, and iv) experienced labor force around the mill. Ethanol yields through enzymatic hydrolysis of pretreated fibers were highest in natural mixed hardwood and eucalyptus (280-285 liters of ethanol per dry ton of biomass) and lowest in loblolly pine (273 liters per dry ton of biomass). Natural hardwood and eucalyptus in the repurposing scenario form the most profitable combinations with an IRR of about 19%, mainly due to low capital expenditure (CAPEX) (per liter of ethanol), low enzyme costs, and higher ethanol yield (compared to loblolly pine). Production cost (in the repurposing scenario) was estimated at \$2.51 per gallon of ethanol (or \$0.66 per liter), cash cost at \$2.14 gallon-1 (or \$0.57 per liter), and CAPEX at \$3.15 gallon-1 (or \$0.83 per liter). Repurposing existing closed mills creates a potential alternative to ramp up in the task of producing alternative lignocellulosic biofuels.

Keywords: Green liquor; Eucalyptus; Hardwood; Pine; Ethanol; Pretreatment

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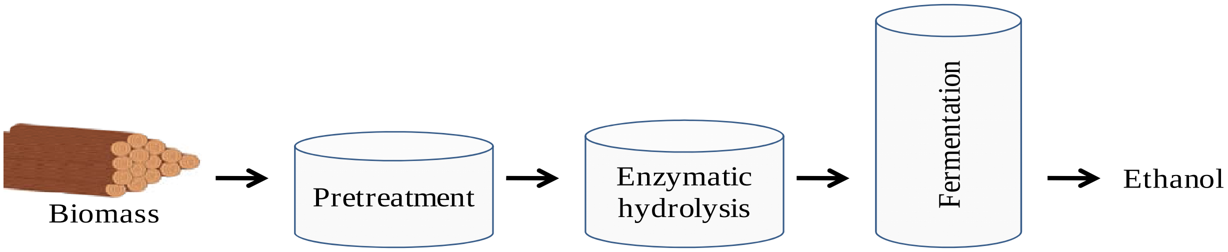
INTRODUCTION

Despite unprecedented incentives and investments by both private and government entities, there is not a single commercial facility producing lignocellulosic ethanol in the U.S., as of the 4th quarter of 2010. The Environmental Protection Agency (EPA) has set ambitious cellulosic biofuel production targets of 0.25 billion gallons (BG) for 2011, 1 BG for 2013, and 16 BG for 2022 (EPA 2010). Several barriers across the entire supply chain have been identified as the major hurdles to profitably producing cellulosic ethanol (Fig. 1). These obstacles are mainly related to lignocellulosic feedstock costs and availability (Bohlmann 2006; Gonzalez et al. 2008; Jackson 2010; Gonzalez et al. 2011a), high pretreatment costs required to lower recalcitrant nature of cellulosic biomass (Overend et al. 1987; Mosier et al. 2003, 2005; Lynd et al. 2008; Gonzalez et al.

2011b,c), high enzyme costs (Wyman 2007, 2008), high capital investment required (Bohlmann 2006; Solomon et al. 2007) and low market ethanol selling price, requiring incentives and subsidies (PEW-CENTER 2010) to achieve competitive financial returns.



Biomass availability, costs, lack of experience in supply chain of bioenergy crops, recalcitrant	**Higher conversion costs due to recalcitrant nature of lignocellulosic biomass. Capital intensive. Pretreatment may destroy some carbohydrate, formation of undesirable by-products**	**High enzyme costs. Current incubation conditions are performed at low solid content. Low efficiency in C_5 conversion. Feed streams must be detoxified**	**Less efficiency in C_5 conversion. CO_2 release is lost carbon not going to product. Product purification may be CAPEX intensive**	**Low market price to achieve competitive return with status quo technology. Tax incentives and subsidies required**

Figure 1. Brief description of major barriers identified in cellulosic ethanol production

When comparing the success of bioethanol production in the U.S. and Brazil, mainly using corn grain and sugar cane as feedstocks, versus the situation of cellulosic ethanol (using mainly lignocellulosic feedstocks such as grasses, agriculture residues and forest biomass), major differences exist with respect to byproduct value, manufacturing, and pretreatment/conversion costs. The corn ethanol conversion processes produces several byproducts, such as protein, oil, corn steep liquid, gluten, and dry distilled grains, all of which have an existing market (RFA 2010; Wu et al. 2010). On the other hand, though technical/economic analyses of cellulosic ethanol have highlighted the importance of recovering all major lignocellulosic components to offset high feedstock cost (Gregg and Saddler 1996a,b), commercial byproducts of lignocellulosic ethanol processes are minimal thus far. Researchers are working to find possible uses of hemicelluloses in the manufacture of polymers and identifying more profitable uses of lignin, other than heat-steam-power generation (Pan et al. 2005a,b; Janssen et al. 2008; Janssen and Stuart 2010). The production of marketable byproducts is of great importance for the economy of the biorefinery. In addition, it is well known that conversion costs are higher for lignocellulosic biomass (compared to corn and sugar cane ethanol), mainly due to its natural resistance to enzymatic hydrolysis (Mosier et al. 2005; Pan et al. 2005a; Wyman et al. 2005). Characteristics of biomass that affect enzymatic digestibility have been the subject of intense research with special interest in cellulose crystallinity, degree of polymerization, specific surface area, carbohydrate-lignin complexes, and degree of hemicelluloses acetylation (Zheng et al. 2009). Significant resources have been committed to understanding the recalcitrance of lignocellulosic biomass, as well as in designing low CAPEX (capital expenditure) and low OPEX (operational expenditure) pretreatment process. Although many pretreatment methods have been developed and are in pilot demonstration, this necessary stage of conversion still represents one of the major technological challenges for ethanol commercialization (Wu et al. 2010).

Pretreatments can be divided into three major groups: physical, chemical, and biological. Physical pretreatments include chipping, grinding, and milling the biomass to reduce particle size. However, some have argued that the energy requirement for such a process is unfeasible (Jin et al. 2010). Biological pretreatments include the use of lignin-degrading microorganisms. This type of pretreatment is considered environmentally friendly and consumes small amounts of energy, relative to physical pretreatments. Nevertheless, biological pretreatments are not practical on an industrial scale because of long residence times, as well as the loss of C_5 and C_6 sugars along with the lignin (Lee 1997; Walton 2010; Jin et al. 2010). Chemical pathways include pretreatments under alkaline and/or acidic media, used to increase accessibility to the cellulose (Yang et al. 2002; Mosier et al. 2005; Wu et al. 2010). Chemical pretreatments are believed to be the most promising pathway for commercial application, but barriers still exist in the form of uncertainty about equipment scale-up (Boerrigter 2006) and the need for additional capital expenditures for chemical recovery (required for both economic and environmental reasons) (Zheng et al. 2009).

Objective

This paper focuses on the economics of producing cellulosic ethanol using green liquor; this is a novel pretreatment process based on a proven technology currently used in hundreds of kraft pulp mills around the world. Green liquor is an alkaline intermediate in kraft pulping; it is composed of *ca.* 75% Na_2CO_3 and 25% Na_2S, and its recovery process in the mill has been successfully practiced over many years. The green liquor process can be used as a potential pathway to pre-treat lignocellulosic feedstock for ethanol production. Previous pretreatment studies with green liquor have been shown to achieve competitive carbohydrate recovery (percentage of carbohydrates in wood that are converted to monomeric sugars) in hardwood (>80%) and softwood (>70%) (Jin et al. 2010; Wu et al. 2010). Other attractive features of this pathway include both the necessary technology already being in place and the already available experience in equipment scale-up and operations. Green liquor has also been used in hemicellulose extraction prior to pulping (Um and van Walsum 2009; Walton 2010; Um and van Walsum 2010) and as a pretreatment prior to pulping to improve kraft pulp yield (Ban and Lucia 2003). The concept of green liquor pretreatment in a repurposed kraft mill is based on the idea of converting existing closed and old kraft pulp mills (closed due to economic conditions) into biorefineries for ethanol production. The financial impact of considering the repurposing concept is analyzed in comparison to a greenfield scenario. Detailed financial analysis, CAPEX, and sensitivity analysis are presented considering three biomass types: southern mixed hardwood, loblolly pine, and *Eucalyptus sp.*

MATERIAL AND METHODS

Green Liquor Pretreatment

As previously discussed, green liquor is a mixture of sodium carbonate and sodium hydroxide. It is inherently produced during the chemical recovery process in kraft pulp mills when spent cooking black liquor is burned in the recovery boiler, producing a water-soluble smelt of sodium carbonate and sodium sulfide. When dissolved in water, green liquor is produced. Chemical recovery is proven, and with the technology already in place, green liquor provides major advantages when compared to other emerging technologies. The overall proposed pathway is illustrated in Fig. 2. Biomass is chipped and fed into a pulp digester with conditions as described in previous studies (Jin et al. 2010; Wu et al. 2010). After pulping, the slurry is washed in vacuum filters, with two streams coming out of this process unit: i) weak black liquor and ii) washed pulp. Weak black liquor contains dissolved organic material, lignin, and cooking chemicals. The solids content of weak black liquor is increased by means of evaporators (using fresh steam from the recovery boiler), and the resulting black liquor is fed with lignin (coming from a downstream lignin filter) into the recovery boiler, where it is burned to produce steam (for power and process steam) and to begin the chemical recovery process. The smelt from the recovery boiler is dissolved in water, producing green liquor. Following the pathway for ethanol production, the pulp (after washing) is fibrillated using refiners commonly found in pulp and paper mills (post-treatment stage). After mechanical treatment in the refiners, to increase accessible surface area, the pulp is further delignified using molecular oxygen and sodium hydroxide as a catalyst (post-treatment stage). Oxygen delignification is highly selective and removes lignin without destroying carbohydrates. The pulp is then enzymatically hydrolyzed for 48 hours as described by Jin et al. (2010). After hydrolysis, the remaining lignin is filtered (and sent to the recovery boiler) and separated from the monomeric stream, which is subsequently fermented and dehydrated to produce 99% ethanol as a final product.

Basis for Evaluation

A total of six cases were evaluated (Table 1), representing combinations of: i) three feedstocks (mixed natural hardwood, *Eucalyptus*, and loblolly pine), ii) green liquor pretreatment for all cases, and iii) the two scenarios of a greenfield pulp mill and a repurposed mill. Additional sensitivity analyses are presented later.

Table 1. Basis for Evaluation

Case\Combination	I	II	III	IV	V	VI
Technology	GL	GL	GL	GL	GL	GL
Raw material	N. hardwood	N. hardwood	Eucalyptus	Eucalyptus	Pine	Pine
Financial scenarios	Greenfield	Repurposing	Greenfield	Repurposing	Greenfield	Repurposing

GL = Green liquor; N. Hardwood = Natural hardwood

Feedstock

Three forestry feedstocks were used as raw material in this economic conversion analysis: southern mixed hardwood, loblolly pine, and *Eucalyptus sp*. The chemical composition assumed for each feedstock is presented in Table 2. Mixed hardwood and loblolly pine are abundant feedstocks naturally occurring in the southern U.S. These raw materials currently supply the region's forest product industry and constitute a well-established supply chain. Genetically improved, fast growing, and cold-resistant *Eucalyptus sp*, has been recently introduced to the southern U.S. by ArborGen (Gonzalez et al. 2008; Hinchee et al. 2009; Gonzalez et al. 2011a,b). These three feedstocks represent current and potential forest biomass assets for conversion into liquid biofuel.

Feedstock cost for each biomass has been assumed and estimated as follows: mixed southern hardwood at $71 per dry metric ton (dry ton), loblolly pine at $69.40 per dry ton, and *Eucalyptus sp.* at $69.40 per dry ton. The estimated delivered biomass cost was based on the productivity, rotation length, moisture content, covered area, and annual supply as presented in Table 3. The method implemented to estimate delivered biomass cost is similar to the method used by Gonzalez et al. (2011). For loblolly pine and *Eucalyptus*, the following items were considered when estimating delivered biomass cost: plantation establishment and maintenance cost (ensuring a 6% internal rate of return (IRR) to the farmer), harvesting cost (estimating an 8% IRR to the harvesting contractor), and freight cost using market values. For natural mixed hardwood, all analyses were the same, except for the stumpage cost, which was assumed at 80% of pulpwood stumpage market price (F2M 2010).

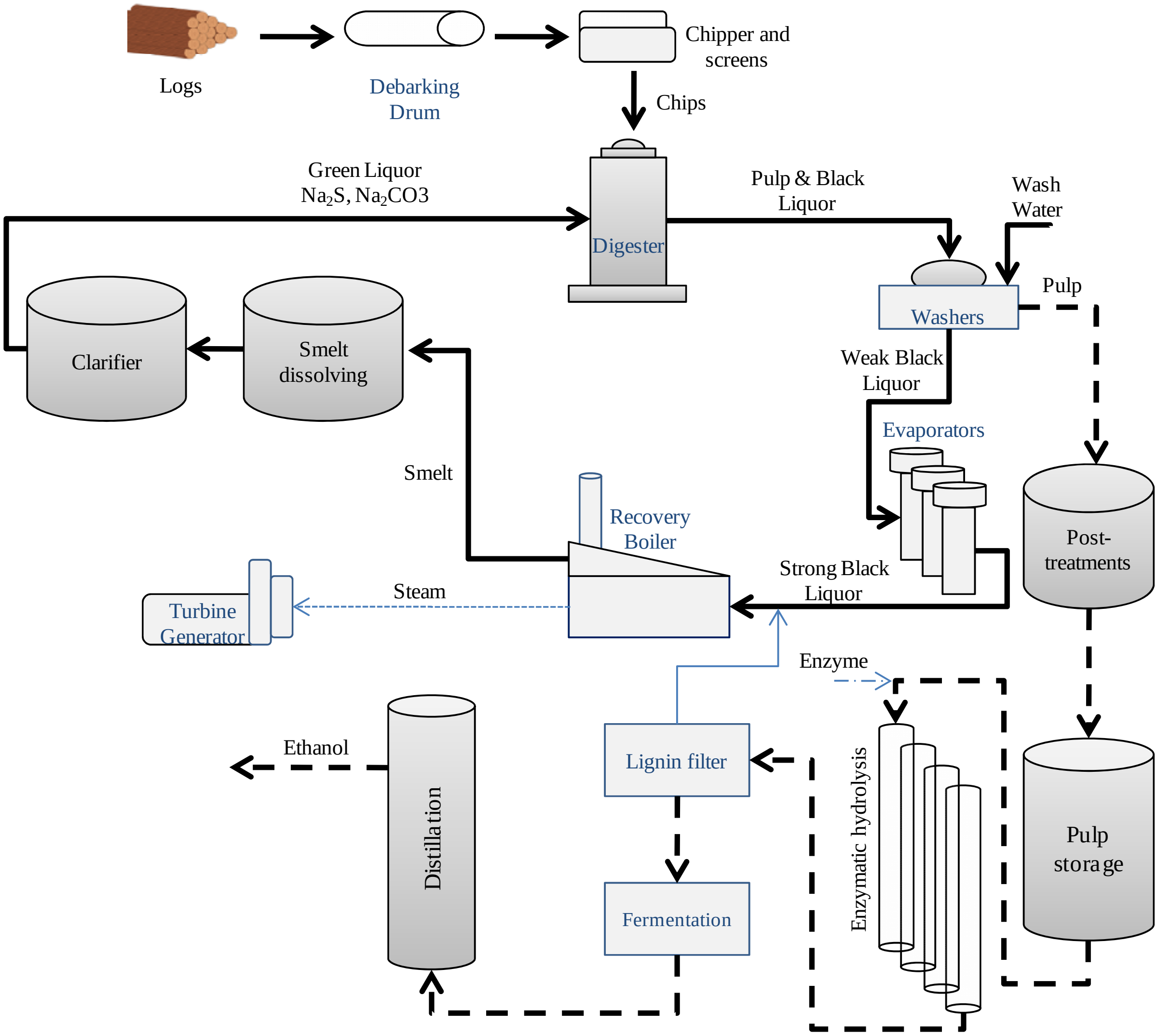


Figure 2. Illustration of green liquor pretreatment process for ethanol production

Table 2. Chemical Constituents of Southern Mixed Hardwood, Loblolly Pine, and *Eucalyptus sp.*

Composition	[1] Southern mixed hardwood	[2] Loblolly Pine	[3] *Eucalyptus sp*
Glucans	42.6%	43.6%	46.7%
Xylans	15.1%	6.6%	12.3%
Galactans	1.0%	2.2%	0.7%
Mannans	2.1%	10.8%	0.6%
Arabinans	0.5%	1.6%	0.2%
Uronic acid	4.7%	3.7%	4.4%
Acetyl	2.7%	1.1%	2.8%
Lignin	28.3%	26.8%	29.4%
Resins	2.5%	3.2%	3.1%
Ash	0.3%	0.4%	0.1%

Source: [1] (Tunc and van Heiningen 2008), [2] (Frederick et al. 2008), [3](Gomides et al. 2006).

CAPEX

Capital expenditure (CAPEX), which represents all capital spending in equipment and structure is summarized in Table 4. All equipment costs have been estimated until year 2012 and sized for an equivalent dry biomass flow of 453,597 dry tons (or 500,000 dry short tons). Two investment scenarios are illustrated: greenfield and repurposing. Greenfield includes all investment associated with land purchase and preparation, equipment, and buildings for a brand new facility with a total CAPEX of ca. $311 million. CAPEX for the greenfield cases are very similar for the three feedstocks considered. Total CAPEX in the repurposing scenario is estimated at around $106 million. The lower CAPEX in the repurposing scenario (compared to the greenfield scenario) is mainly due to the fact that existing equipment and buildings in the closed kraft pulp mill resemble most of the equipment required in the greenfield facility.

Table 3. Delivered Cost, Rotation Length, Productivity, Moisture Content, Covered Area, and Annual Supply Assumed for Natural Mixed Hardwood, *Eucalyptus sp.*, and Loblolly Pine

Biomass	Natural hardwood	Eucalyptus	Pine
$/dry ton	71.0	69.4	69.4
Rotation length (years)	-	4	11
Productivity (dry ton/acre/yr)	2.2	20.2	17.0
Moisture content (%)	45%	45%	45%
Covered area (%)	5%	5%	5%
Supply (dry ton/year)	453,597	453,597	453,597

Table 4. Capital Expenditure for the Biorefinery, Greenfield, and Repurposing

Area	Scale factor	Greenfield (US$)	Repurposing (US$)	Source
Site preparation				
Land purchase	0.9	1,238,934		1
Land preparation	0.9	14,867,211		1
Raw water treatment	0.7	1,447,504		1
Waste water treatment	0.7	2,171,256		1
Roundwood receiving				
Chip receiving		17,745,379	17,745,379	1
Pretreatment				
Green liquor pretreatment	0.6	30,373,350		1
Post Treatment				
Mechanical post treatment	0.6	5,528,526	5,528,526	1
Oxygen post treatment	0.6	18,597,603	18,597,603	1
Enzyme post treatment	0.5	48,619,292		1
Lignin filter	0.6	12,525,287	12,525,287	2
Biorefinery				
Fermentation	0.8	22,074,022	22,074,022	3
Beer column	0.8	5,011,199	5,011,199	3
Rectification column	0.8	4,653,067	4,653,067	3
Dehydration	0.7	5,139,166	5,139,166	3
Product storage & shipment	0.6	4,718,604	4,718,604	3
Yeast preparation				
Recovery and power				
Evaporation	0.6	28,409,692		1
Recovery boiler	0.6	59,475,156		1
Turbine generator	0.5	28,100,034		1
Other			10,000,000	1
Total CAPEX		**310,695,283**	**105,992,853**	

Source: [1] (Annonymous 2010), [2] (Annonymous 2010), [3](Aden, Ruth et al. 2002)

New investments in the repurposing scenario are required in wood chips receiving, mechanical and chemical post-treatments (refining and oxygen delignification, respectively), and lignin filters. Investment in fermentation and dehydration assets is required in both scenarios.

General Assumptions

Table 5 lists the major assumptions used in the technical/economic analysis. Listed input data are related to: financial evaluation horizon of the project (15 years), CAPEX spending schedule, working capital, tax rate, discount rate, revenue for ethanol selling, subsidies, and others (see Table 5 for further detail). Most of the inputs assumed are standards for the three feedstocks considered, except for enzyme and chemical costs (both in $ per liter of ethanol). Enzyme costs are assumed to be different, primarily because of the enzyme charge required to achieve targeted polymer-to-monomer conversion. Differences in enzyme doses are due to varying recalcitrance of each biomass. Enzyme dosages are obtained from laboratory experiments and literature review (see enzyme dosage and cost section for further information) (Jin et al. 2010; Kazi et al. 2010; Wu et al. 2010). Costs are scaled at 3% per year. Ethanol revenue ($ per liter of ethanol) is assumed to increase 2% per year with the ethanol subsidy being held constant throughout the project lifetime.

Enzyme Costs and Dosage

Enzyme cost was assumed at $1.85 per kg of enzyme (Bryant 2010). Enzyme doses modeled for our analysis are presented in Table 6. The conversion between enzyme dose g/g of cellulose and FPU/g of cellulose was done following the methodology used by Kazi et al. (2010). Enzymatic charge was based on enzymatic hydrolysis lab results (Jin et al. 2010; Wu et al. 2010). Enzyme activity is estimated to be 85 FPU per gram of enzyme. The enzyme dose for *Eucalyptus* was assumed similar to mixed hardwood, while twice the dose is needed to achieve 80% of enzyme hydrolysis of loblolly pine.

Table 5. Modeled Chemical and Enzyme Cost, and Major Assumptions Used in the Economic Analysis

Description	Value	Description	Value
Startup year	2012	(non-maintenance), $/hr	120
Terminal year	2026	Salaried staff, $/hr	24
Plant & equipment scaleup exponent	0.70	% of replacement asset value	2%
CAPEX spending		Capital reinvestment, % of replacement asset value	1%
% of spending in year -2	30%	Other fixed costs, % of sales	3%
% of spending in year -1	50%	Sales and other overhead, % of sales	3%
% of spending in year -0	20%	Gas cost, $ per MMBTU	4.5
% of nominal capacity, project year 1	50%	Enzyme cost, $ per liter ethanol, M. hardwood	0.15
% of nominal capacity, project year 2	80%	Enzyme cost, $ per liter ethanol, Eucalyptus	0.16
Excess Material Use in Project year 1	0.3	Enzyme cost, $ per liter ethanol, Loblolly pine	0.31
presubsidy product revenue	10%	Chemical cost, $ per liter ethanol, M. hardwood	0.01
Years depreciation schedule, straight line	10	Chemical cost, $ per liter ethanol, Eucalyptus	0.01
Tax rate, with tax loss carryforward	35%	Chemical cost, $ per liter ethanol, Loblolly Pine	0.01
Discount rate	12%	Yeast cost, $ per liter ethanol	0.02
Terminal value, year 15 EBITDA multiple X	5	Caustic Soda, $ per Ton (100%)	441
Hours per year	8400	Sodium Carbonate, $ per Ton (100%)	220
Revenue per liter of ethanol	0.5283	Sodium Sulfate, $ per Ton (100%)	441
Subsidy added to price, $ per liter ethanol	0.2668	Ammonia, $ per Ton (100%)	220
Subsidy, tax credit	0.5	Sulfuric Acid, $ per Ton (100%)	441
Power, $ per MWH	50	Lime, $ per Ton (100%)	220

Table 6. Enzyme Doses for Each Biomass

Feedstock	Enzyme dose (g/g cellulose)	Relative dose charge, based on M. hardwood
M. hardwood	0.059	1
Eucalyptus	0.059	1
Loblolly pine	0.118	2

Reaction Yield and Conversion Factors

Reaction yield and conversion factors assumed for the economic analysis for the three feedstocks are displayed in Table 7. As illustrated in Table 7, #1 represents yield factor assumed for loblolly pine exclusively, #2 contains conversion factors for both mixed hardwood and *Eucalyptus*, and #3 lists conversion factors for all three feedstocks. Washing efficiency in the lignin filter is assumed to be 95%, meaning that 5% of monomeric sugars are lost with lignin and other dissolved organics. Consistency of cake solids after lignin filter is assumed to be 50%. Fermentation efficiencies for C_6 and C_5 sugars were assumed to be 95% and 80% respectively. Stoichiometric conversion of monomeric sugars to ethanol was assumed at 51% (see Table 5 for more details).

Table 7. Reaction Yields and Conversion Factors

		Components					
	Process	**Lignin**	**Glucan**	**Hexan**	**Xylan**	**Extractives**	**Ash**
1	Green liquor pretreatment	90%	90%	50%	80%	50%	50%
	Chemical post-treatment	80%	98%	96%	96%	50%	50%
2	Green liquor pretreatment	92%	91%	38%	80%	50%	50%
	Chemical post-treatment	80%	98%	98%	98%	50%	50%
3	Enzymatic hydrolysis		80%	80%	80%		100%
	Hydration factor		111%	111%	114%		
	Lignin filter efficiency		95%	95%	95%		
	Fermentation efficiency		95%	95%	80%		
	Fermentation stoichiometry		51%	51%	51%		

1 =Loblolly pine; 2= Mixed hardwood and *Eucalyptus*; 3= Pine, mixed hardwood and *Eucalyptus*

Process Simulation

A complete process model for the green liquor pretreatment biorefinery was produced using WinGEMS v5.3. This process simulation software was originally developed for use in the pulp and paper industry and therefore has specialty blocks and units operations, (such as chemical recovery equipment and reactions) particularly useful for application in a pulp and paper mill. The process simulation model produced steadystate mass and energy balances for the entire facility. This information was exported to a spreadsheet by interface with Microsoft Excel, where it could easily be referenced during the economic evaluation of the project.

RESULTS AND DISCUSSION

Production Costs

Production cost, cost drivers, and cash costs in $ per gallon of ethanol are depicted for each combination in Table 8. Production costs are similar for all cases except for enzyme, energy, and depreciation, which are different mainly because of enzyme dose, lignin content, and CAPEX, respectively. Enzyme cost is considerably higher for pine, due to its recalcitrance (compared to more easily hydrolyzed raw materials, such as natural hardwood). In the case of pine, enzyme cost represents one third of total production cost, while it is around 17% to 22% of hardwood production costs. Lower CAPEX in the repurposing scenarios results in a lower depreciation per gallon of ethanol. Natural hardwood and *Eucalyptus* in the repurposing scenarios have lower production costs and cash costs. The most costly option is the greenfield investment scenario, especially with loblolly pine. Values have been provided in dollars per gallon as some values will be very minimal in a dollar per liter basis.

Table 8. Reaction Yields and Conversion Factors

Cost drivers	N. hardwood Greenfield	N. hardwood Repurposing	Eucalyptus Greenfield	Eucalyptus Repurposing	Pine Greenfield	Pine Repurposing
Ethanol revenue ($/gallon)	2.08	2.08	2.08	2.08	2.08	2.08
Ethanol subsidy ($/gallon)	1.01	1.01	1.01	1.01	1.01	1.01
Wood ($/gallon)	-1.00	-1.00	-0.96	-0.96	-1.00	-1.00
Chemicals ($/gallon)	-0.04	-0.04	-0.04	-0.04	-0.05	-0.05
Yeast ($/gallon)	-0.07	-0.07	-0.07	-0.07	-0.07	-0.07
Enzymes ($/gallon)	-0.55	-0.55	-0.59	-0.59	-1.14	-1.14
Energy ($/gallon)	0.04	0.04	0.03	0.03	0.07	0.07
Depreciation ($/gallon)	-0.91	-0.31	-0.90	-0.31	-0.94	-0.31
Labor, overhead, others ($/gallon)	-0.63	-0.58	-0.62	-0.58	-0.64	-0.59
Production cost ($/gallon)	-3.15	-2.51	-3.14	-2.51	-3.76	-3.09
Cash cost ($/gallon)	-2.18	-2.14	2.19	-2.14	-2.76	-2.71

1 gallon = 3.7584 liters

Total production costs for natural mixed hardwood in the repurposing green liquor scenario are illustrated in Fig. 3. The four largest cost drivers are raw materials (ca. 40%), enzymes (21.8%), labor & overhead (23.2%), and depreciation (12.3%). Raw materials and enzymes together account for ca. 61.6% of the total cash cost. Chemicals are not an important cost share, mainly due to the chemical recovery feature of the green liquor process. All combinations of biomass and pretreatment were energy self-sufficient; they generated energy with the steam coming from the recovery boiler.

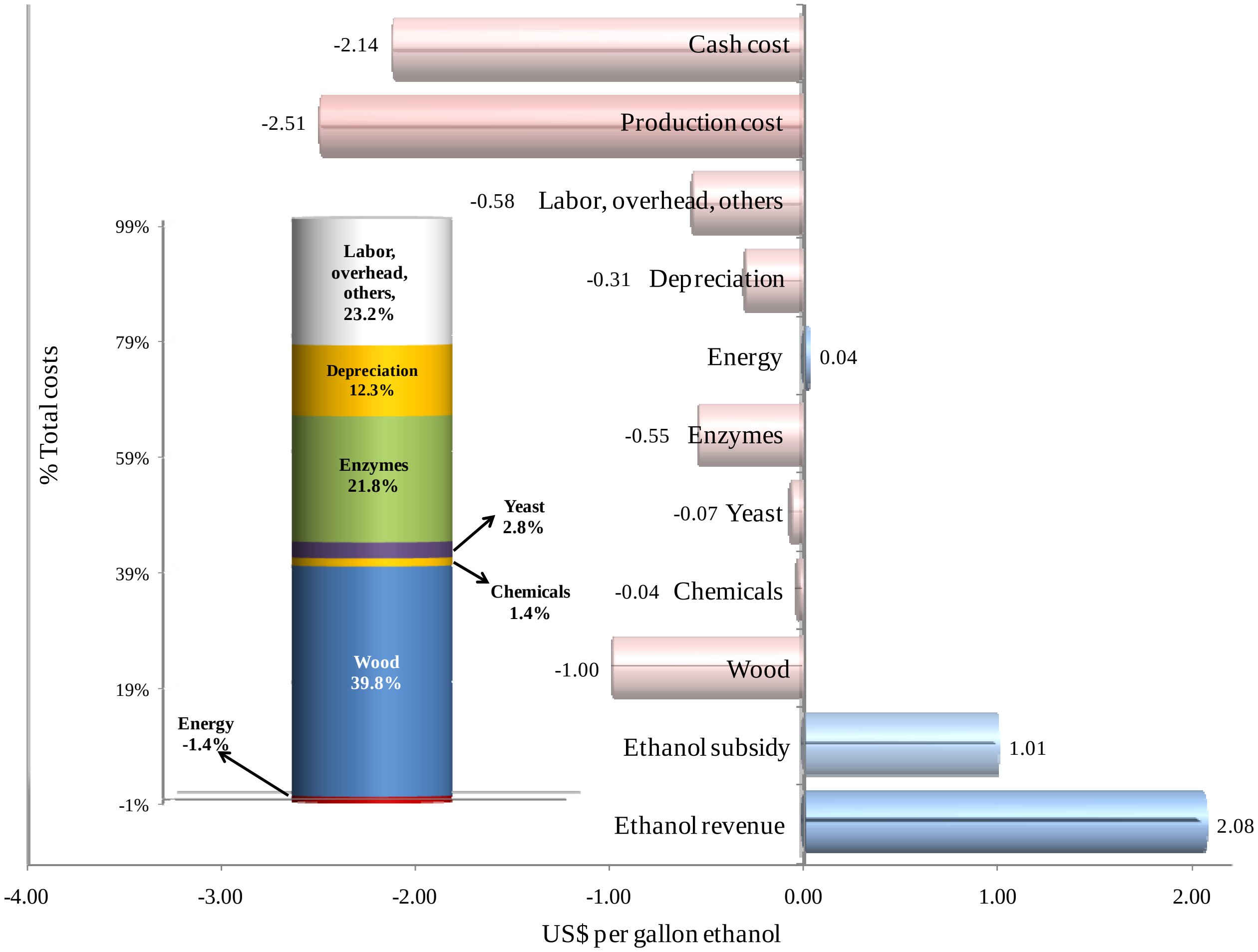


Figure 3. Production costs, cash cost and, share cost of ethanol for natural mixed hardwood in the repurposing green liquor scenario.

Financial Indicators

Financial indicators (net present value and internal rate of return) for the three feestocks and investment scenarios are illustrated in Fig. 4. Only two combinations showed positive returns, (both in the repurposing scenarios) which are natural hardwood (NPV $64 million, IRR 19.1%) and *Eucalyptus* (NPV $66 million and IRR 19.2%). Loblolly pine is the least attractive biomass in both greenfield (NPV -$205 million) and repurposing (NPV -$22 million and IRR 9.4%). For all cases, the repurposing scenario is the most profitable.

The financial performances for the three feedstocks and two investment scenarios are explained in Fig. 5, where total CAPEX and CAPEX per annual liter of ethanol are depicted. As expected, the greenfield scenario has a higher CAPEX, with total CAPEX ranging from $310 million to $312 million, resulting in a CAPEX ranging from ca. $2.40 to $2.50 per liter of ethanol. The repurposing scenarios show the lowest CAPEX with values between $104 million and $106 million, resulting in a CAPEX of $0.80 per liter.

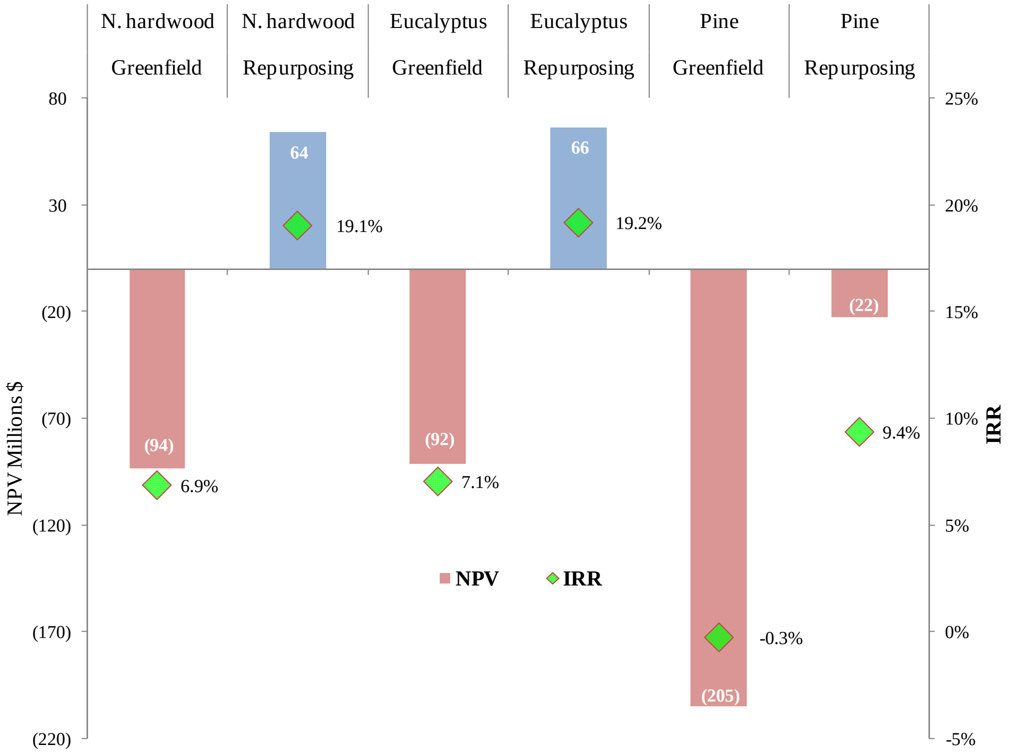


Figure 4. NPV and IRR for the six combinations of biomass and investment scenarios

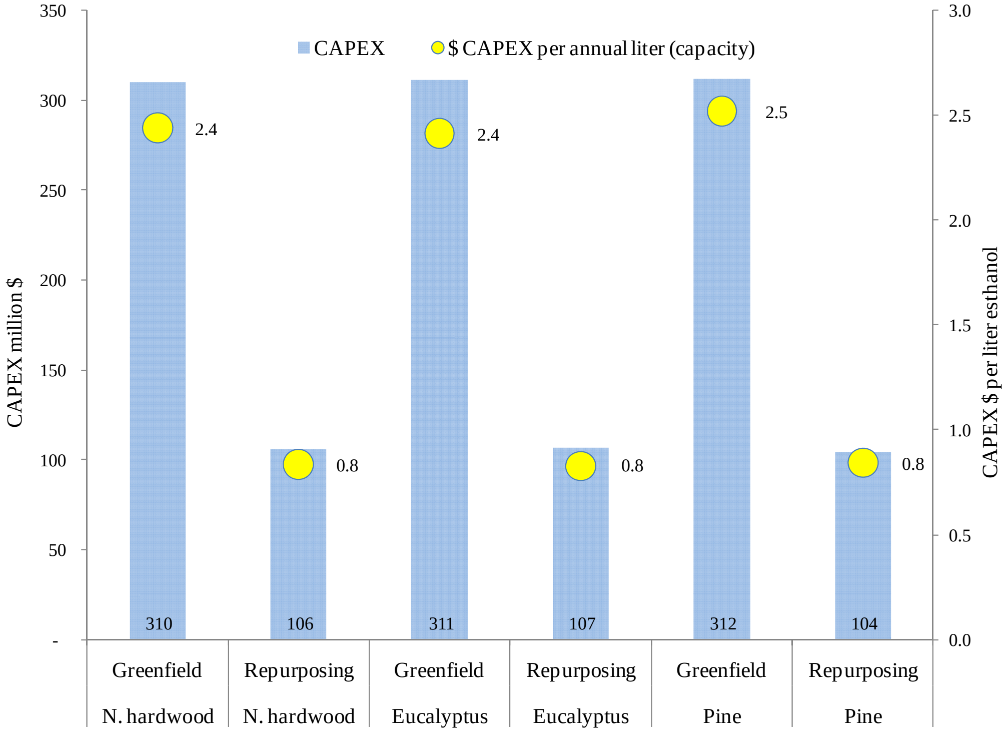


Figure 5. Total CAPEX and CAPEX per liter of ethanol for the six biomass and investment combinations.

Ethanol Yield

Ethanol yield, CAPEX per liter of ethanol, and the payback of the investment are presented for each biomass and investment scenario in Fig. 6. Payback is the number of years required to offset the total investment, so that the accumulated free cash flow (at historical values) becomes positive (Ross et al. 2004). Lower payback is found in the repurposing scenarios, mainly in natural hardwood and *Eucalyptus*, where ethanol yields are higher. Ethanol yield (liter of ethanol per dry metric ton of biomass) is highest in *Eucalyptus* (285 liter dry ton^{-1}), followed by natural hardwood (280 liters dry ton^{-1}), and lowest in Loblolly pine (273 liter dry ton^{-1}). Ethanol yield depends on the carbohydrate content found in the biomass and pretreatment yield (Gonzalez et al. 2011). Ease of biomass conversion (polymeric to monomeric sugars) will influence the severity of the pretreatment and therefore the amount of monomeric sugars available for fermentation after enzymatic hydrolysis.

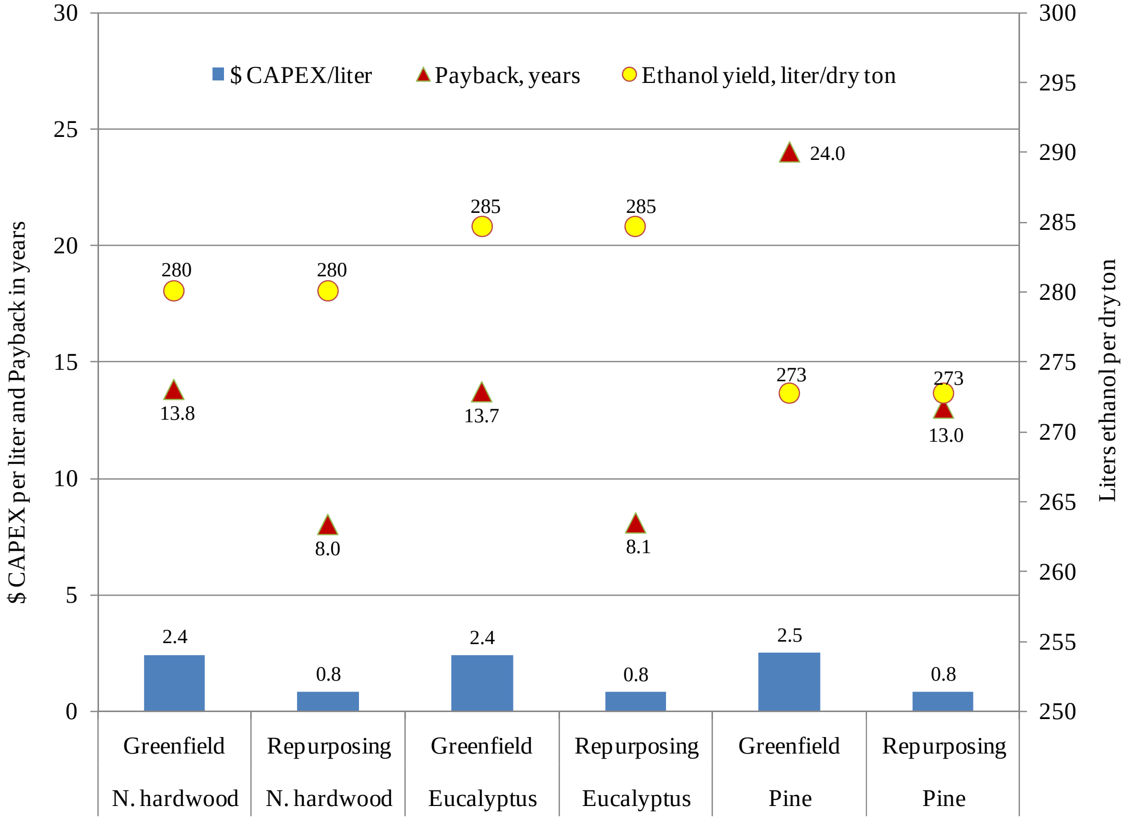


Figure 6. Ethanol yield, CAPEX per liter of ethanol, and payback for each biomass and investment combination.

Sensitivity Analysis

A sensitivity analysis was performed for the most profitable scenario, mixed natural hardwood (Fig. 7), to understand how changes in CAPEX, ethanol yield, biomass cost, and enzyme cost affect the profitability of the project, specifically the net present value (NPV). This analysis includes a variation of +/- 25% of the central assumptions listed in methodology section. Ethanol yield has the highest impact on the NPV of the biorefinery. Biomass and enzyme costs represent the second set of most significant sensitivities. A variation of +/- 25% in the CAPEX of the project affected NPV the least.

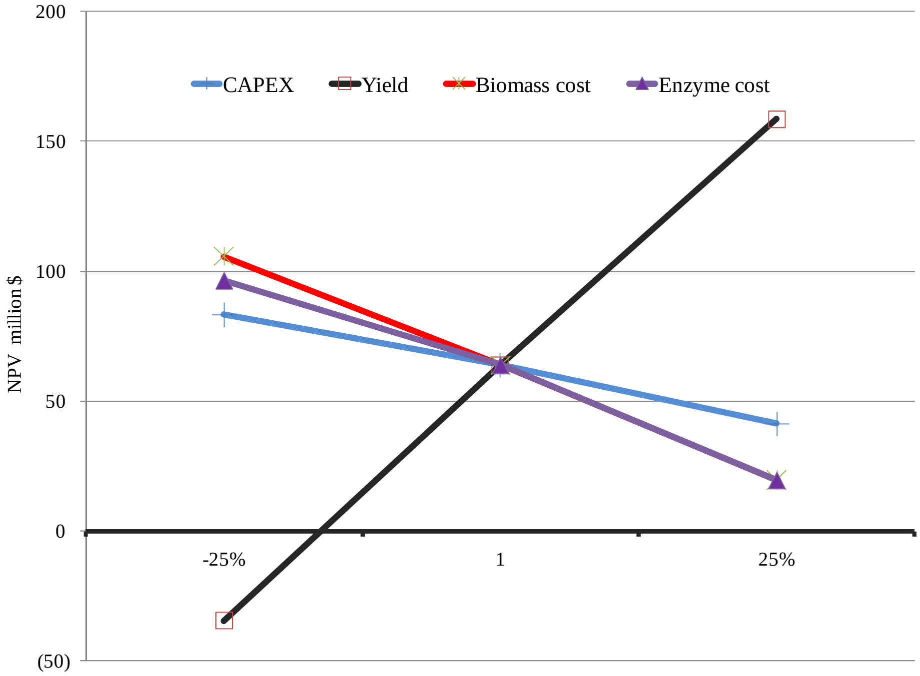


Figure 7. Sensitivity analysis +/- 25% of CAPEX, yield (liter ethanol/dry ton), biomass cost, and enzyme cost

CONCLUSIONS

Green liquor repurposed pathway is a potential pretreatment for cellulosic ethanol conversion. This technology has several advantages:

- It is a proven technology currently in operation in hundreds of kraft pulp mills around the world
- Green liquor chemical recovery is very well known, which is an advantage for environmental and economical requirements.
- The repurposing concept, the most attractive scenario, is an ideal solution to activate closed operations in regions where the biorefinery can be an important source of employment and development for the economy. This repurposing concept will also take advantage of existing fiber supply chain and an experienced potential work force.
- Existing biomass assets, such as natural hardwood and fast growing species of *Eucalyptus*, are potential feedstocks available for conversion into ethanol. However, reduction in fiber supply cost is important to reduce sourcing risk and improve the economy of the biorefinery.

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Article submitted: April 1, 2011; Peer review completed: April 20, 2011; Revised version received and accepted: May 9, 2011; Published: May 13, 2011.